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Hurricane Wind Speeds in the United States

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HURRICANE WIND SPEEDS IN THE UNITED STATES

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Cover: *Sattelite Photo of Hurricane Frederick, September 19, 1979.*

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NOTATION

dp/dn = pressure gradient

f = Coriolis parameter

K = coefficient

ℓ = angle between storm track and coastline

p = retardation factor

p_n = standard pressure

$P(n,\tau)$ = probability that n storms occur in t years

$P(V < v|n)$ = probability that the wind speed V in n storms is less than v

$P(V < v|\tau)$ = probability that the wind speed V in τ years is less than v

r = distance from storm center

R = radius of maximum wind speeds

s = hurricane translational speed

t = time, in hrs.

V_{gx} = maximum gradient windspeed

$V(z,R)$ = maximum velocity at z meters above ground at the radius of maximum winds

$V(z,r)$ = maximum velocity at z meters above ground at the radius r from the eye

$V(z,r,\theta)$ = velocity at z meters above ground at radius, r and angle θ from OM

z = height above ground or water surface, in meters

α = coefficient

Δp_{max} = pressure drop from periphery of hurricane to its center

ρ = air density

θ = angle between lines ON and OM

ϕ = angle between storm track and coastline

ABSTRACT

A Monte Carlo simulation technique is used to obtain estimates of hurricane wind speeds along the Gulf and East Coasts of the United States. The paper describes the sources of data, the probabilistic models for climatological characteristics of hurricanes, and the physical models for the hurricane wind speed field used in the estimations. Estimated values of fastest-mile hurricane wind speeds at 10 m above ground in open terrain at the coastline and at 200 km inland are given for various mean recurrence intervals. The estimated hurricane wind speeds were found to be best fitted by Weibull distributions with tail length parameters $\gamma \geq 4$. Estimates are given of various errors inherent in the estimated values of the hurricane wind speeds. Owing to uncertainties with respect to the applicability of the physical models used in this work to locations north of Cape Hatteras, estimated hurricane wind speeds given for these locations should be viewed with caution.

Key Words: Buildings (codes); climatology; hurricanes; statistical analysis; structural engineering; tropical cyclones; wind (meteorology).

Facing page: *Damage caused by Hurricane Camille.*

1. INTRODUCTION

It has previously been shown that predictions of extreme wind speeds in hurricane-prone regions cannot in general be based upon the statistical analysis of the largest annual wind speeds recorded at a given site [10, p. 84]. For this reason, estimates of extreme hurricane wind speeds at a site are commonly obtained by indirect methods [1, 4, 11, 12] from (1) statistical information on the climatological characteristics of hurricanes, and (2) a physical model of the hurricane wind structure. The climatological characteristics of hurricanes include: (a) rate of hurricane occurrence in any given region; (b) difference between atmospheric pressures at the center and at the periphery of the storm; (c) radius of maximum wind speeds; (d) speed of storm translation; (e) direction of storm motion, and (f) crossing point coordinate along the coast or on a line normal to the coast. The physical model of the hurricane wind includes assumptions on: (a) dependence of surface wind speeds upon difference between atmospheric pressures at center and periphery of the storm, radius of maximum wind speeds, speed of translation, latitude, and position of the point being considered with respect to center of the storm; (b) storm decay as the storm travels over land and its supply of energy in the form of warm moist air from the ocean surface is

thus cut off; (c) reduction of wind speeds due to friction over land; and (d) ratios between wind speeds averaged over various time intervals.

Given the available statistical information on the climatological characteristics of hurricanes, probabilistic models are estimated for each of these characteristics. A large number of hurricanes is then generated by Monte Carlo simulation (random sampling) from these probabilistic models, as will be explained subsequently in the report. The largest wind speeds occurring within each of these hurricanes at the site of concern are the data from which the cumulative distribution function of the hurricane wind speeds at that site is then estimated. This procedure was first developed by Russell [9], who also developed the computer program used in this work.

The purpose of this paper is to present estimates of hurricane wind speeds on the Gulf and East Coasts of the United States based on the procedure just outlined and on data taken from References 3 and 5. The probabilistic and physical models used to obtain these estimates will be described, and an analysis will be made of errors inherent in the estimates. Estimates of hurricane wind speeds in California [13] are not treated in this report.

Facing page: *Damage to solar collectors, caused by Hurricane Frederick.*

2. PROBABILISTIC AND PHYSICAL MODELS

2.1 PROBABILISTIC MODELS

The following probabilistic models were used:

1. The hurricane occurrence is described by a constant rate Poisson process.

2. The probability distribution of the pressure difference between center and periphery of storm, Δp_{max}, is lognormal. To eliminate values of Δp_{max} judged, in light of historical data [5], to be unrealistically high, the distribution is censored so that $\Delta p_{max} < 101.6$ mm (4.00 in) of mercury. (Note that $\Delta p_{max} \simeq 101.6$ mm corresponds to the lowest atmospheric pressure ever recorded worldwide [14].) The effect of this censoring will be commented upon subsequently in this report.

3. The probability distribution of the radius of maximum wind speeds, R, is lognormal. This distribution is censored so that 8 km < R < 100 km to avoid unrealistically "tight" or "broad" storms [5].

4. The average correlation coefficient between R and Δp_{max} is approximately -0.3 (see Reference 5, pp. 68 and 69). All other climatological characteristics are assumed to be statistically independent.

5. The probability distribution of the speed of translation, s, is normal. This distribution is censored so that 2 km/hr $\leq$ s $\leq$ 65 km/hr [5].

6. The cumulative distribution function of the hurricane crossing point along the coast is a curve matching the historical data as recorded in Reference 5. Separate distribution curves are defined for entering, exiting, upcoast heading, and downcoast heading storms. The length of coast being considered for entering and exiting storms includes a 470 km segment downcoast of the location under investigation, and a 370 km segment upcoast of that location, the influence of storms not crossing these segments being negligible for practical purposes. The downwind and upwind segments are unequal because, owing primarily to the presence of the translational speed of the storm, the hurricane wind structure is asymmetrical. As an example, the distribution curve assumed for entering storms affecting coastal milepost 400 n. mi. (740 km) [see Figure 1] is shown in Figure 2.

7. The crossing points on a line normal to the coast are assumed to be uniformly distributed between 110 km and 280 km from the coast in the case of upcoast heading storms, and between 110 km and 360 km in the case of downcoast heading storms.

8. The cumulative distribution functions of heading (direction of storm translation) for entering storms are curves matching the historical data recorded in Reference 5. As an example, Figure 3 shows the distribution of the storm headings about their mean value for milepost 400 n. mi. (740 km). For exiting storms and for storms crossing a line normal to the coast, the distributions are assumed to be uniform between $\pm$ 30° of the mean. The mean values of the storm headings are obtained from the data of References 3 and 5. In all cases it was assumed that the path of the storm motion is a straight line.

2.2 PHYSICAL MODELS

2.2.1 Maximum Gradient Wind Speed

The maximum gradient wind speed can be written as

$$V_{gx} \simeq -\frac{Rf}{2} + \left(\frac{R}{\rho}\frac{dp}{dn}\right)^{1/2} \quad (1)$$

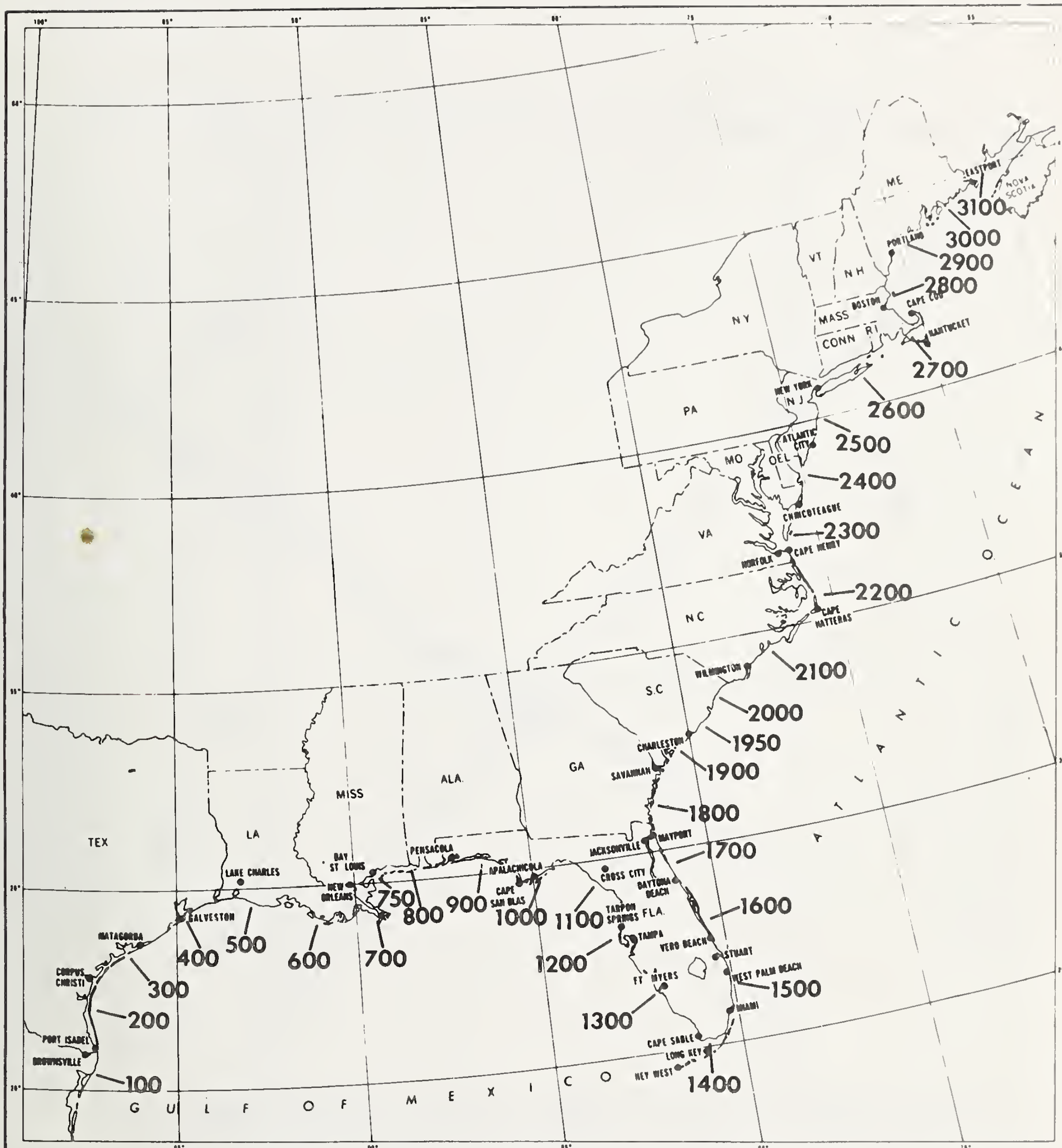


Figure 1. Locator map with coastal distance intervals marked in nautical miles (1 n. mi. ≃ 1.9 km) [5].

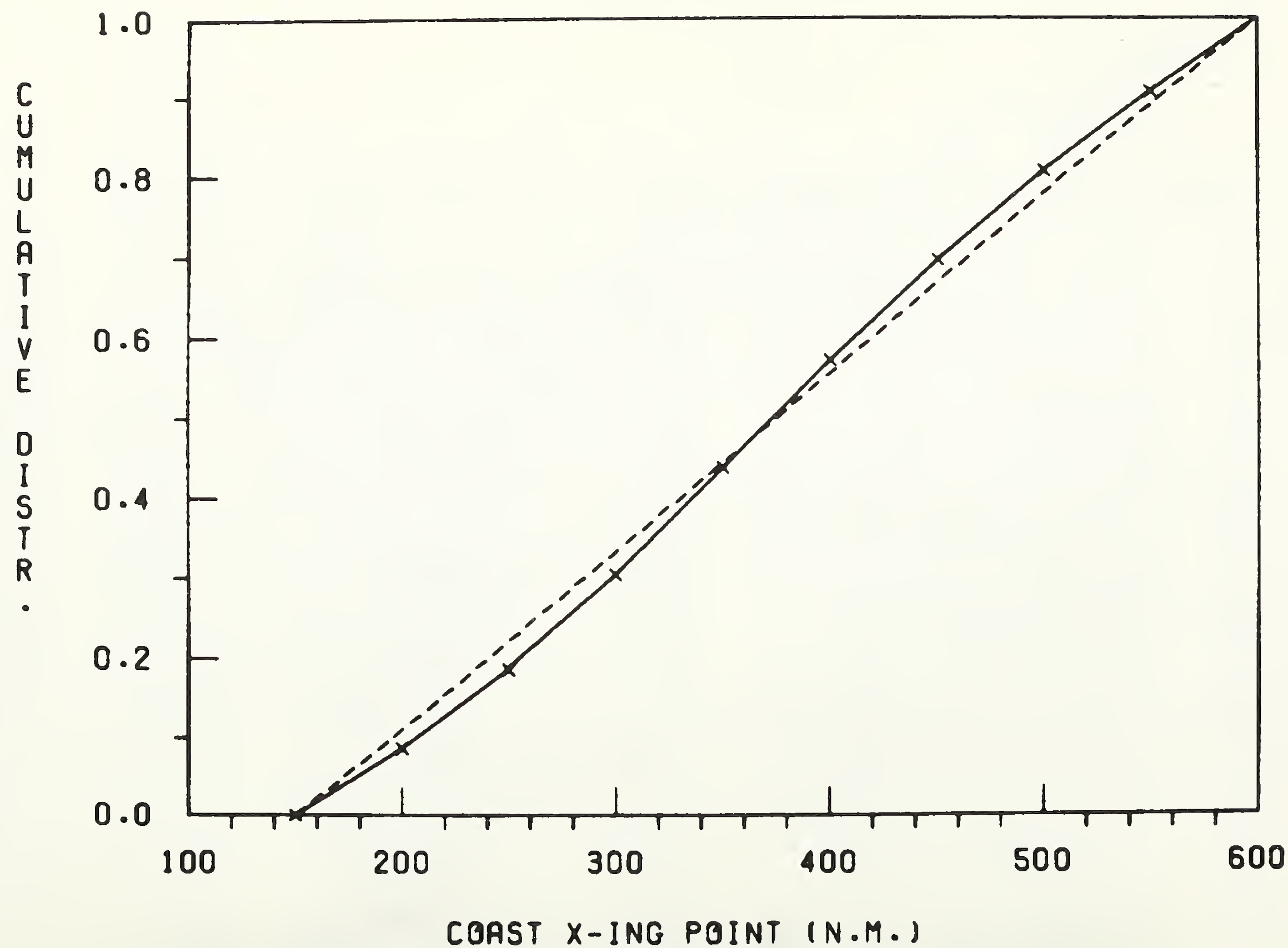


Figure 2. Cumulative distribution function of entering hurricane crossing point, milepost 400 n. mi. (1 n. mi. ≈ 1.9 km).

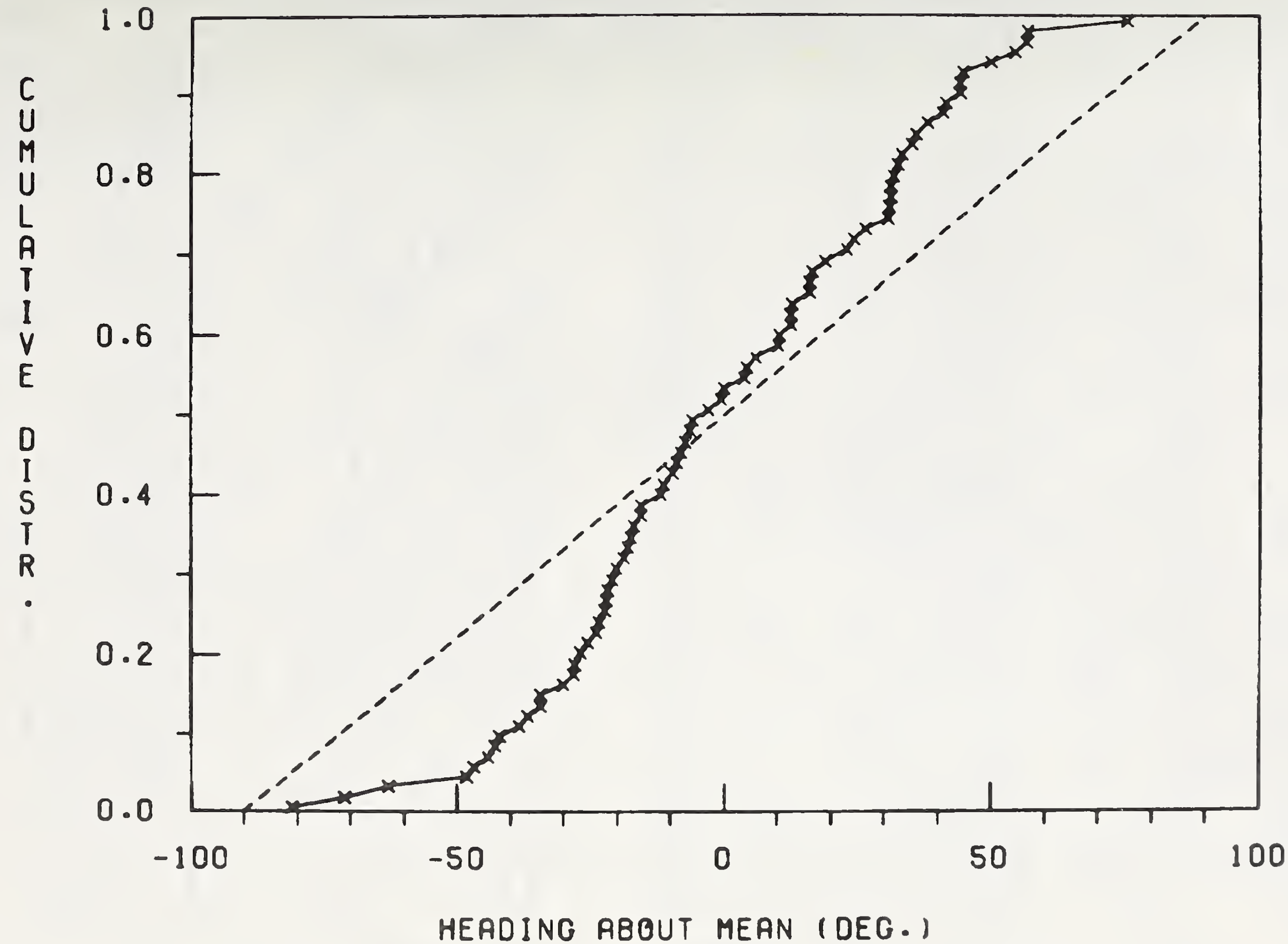


Figure 3. Cumulative distribution function of entering storm headings about mean, milepost 400 n. mi. (1 n. mi. ≈ 1.9 km).

(see Reference 10, p. 18), where f = Coriolis parameter, dp/dn = pressure gradient, ρ = air density, and R = radius of maximum wind speeds. It is reasonable to assume

$$\frac{dp}{dn} = \alpha \Delta_{pmax} \tag{2}$$

where α is a coefficient determined empirically. It then follows from Equations 1 and 2

$$V_{gx} = K \sqrt{\Delta_{pmax}} - \frac{Rf}{2} \tag{3}$$

where the notation $K = [R\ \alpha/\rho]^{1/2}$ is used. Values of K consistent with those determined empirically by the Hydrometeorological Branch (National Weather Service, National Oceanic and Atmospheric Administration) and used in Reference 8 vary approximately between 6.97 m/s/mm$^{1/2}$ (77.5 mph/in$^{1/2}$) at latitude 23°N to 6.93 m/s/mm$^{1/2}$ (77.0 mph/in$^{1/2}$) at latitude 45° N. [These values may be used in conjunction with the assumption that the pressure at the periphery of the storm is p_n = 765 mm (29.77 in).]

2.2.2 Wind Speeds at 10 m Above the Ocean Surface

The maximum wind speed at 10 m above the ocean surface, averaged over 10-min, is assumed to be given by the empirical relation [8]

$$V(z=10,R) = 0.865\ V_{gx} + 0.5\ s \tag{4}$$

Let the center of the storm be denoted by O, and let a line OM be defined that makes an angle of 115° clockwise from the direction of motion of the storm. The 10-min wind speed at 10 m above the ocean surface at a distance r from O along the line OM is denoted by V(z=10, r). The ratio V(z=10,r)/V(z=10,R), is assumed to depend on r as shown in Figure 4 [8]. Let now the angle between a line ON and line OM be denoted by θ. The 10-min wind speed $V(z=10,r,\theta)$ at 10m above the surface at a distance r from the storm center on line ON is assumed to be given by the expression [8]

$$V(z=10,r,\theta) = V(z=10,r) - \frac{s}{2}(1 - \cos\theta) \tag{5}$$

The wind velocity vector has a component directed toward the center of the storm. The angle between that vector and the tangent to the circle centered at O is assumed to be between 0° and 10° in the region $0 < r < R$, between 10° to 25° in the region $R \leq r < 1.2R$, and 25° in the region $r \leq 1.2R$ [8].

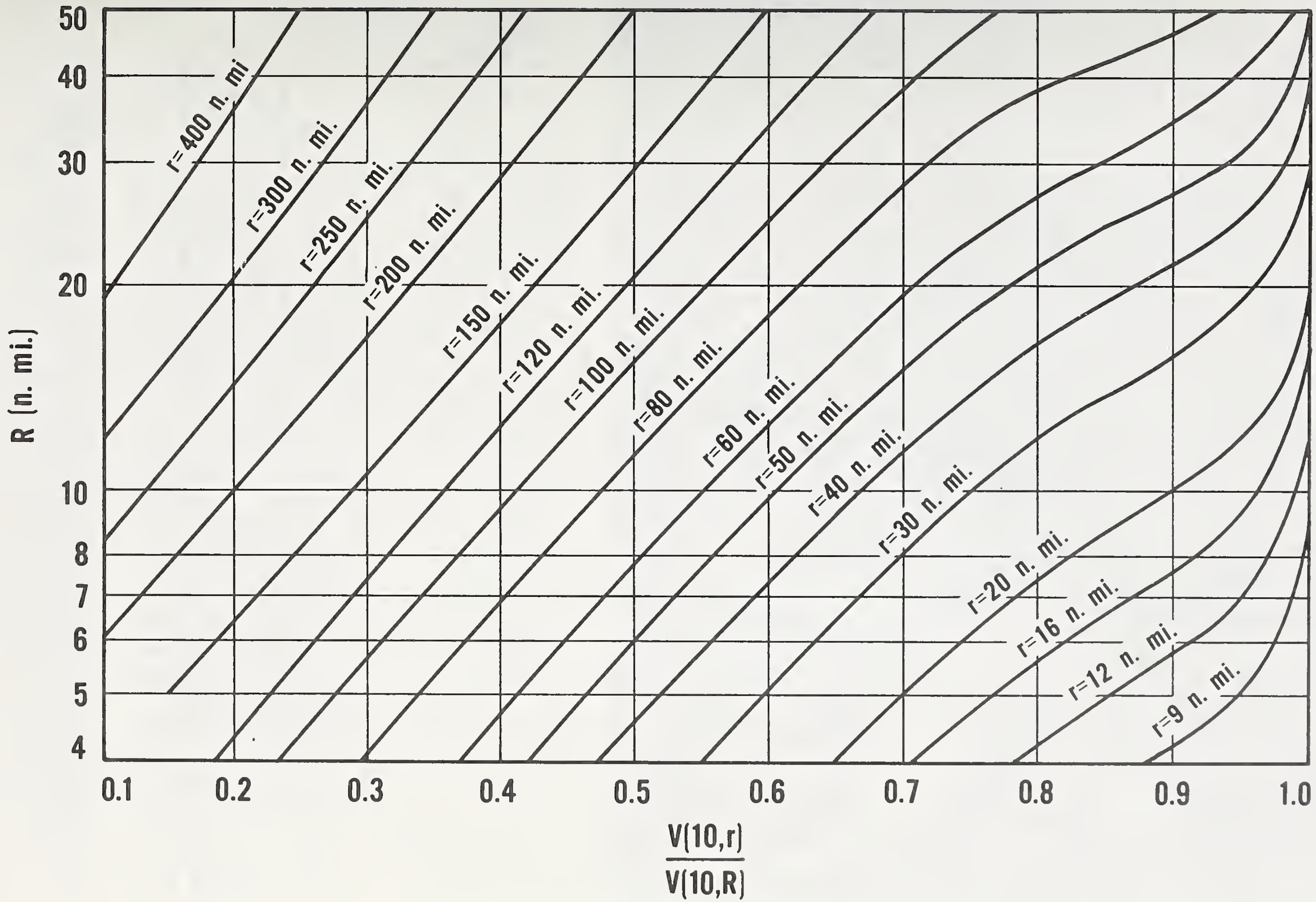


Figure 4. Ratios V(10,r)/V(10,R).

2.2.3 Storm Decay

The storm decay was assumed to result from a decrease with time of the difference between pressure at the center and at the periphery of the storm, given by the following relation

$$\Delta p(t) = \Delta p_{max} - 0.02\ [1+\sin \phi]t \tag{6}$$

where t = travel time in hours, $\Delta p(t)$ and Δp_{max} are given in inches, and ϕ = angle between coast and storm track ($0 < \phi < 180°$). As shown subsequently in this paper, results based on this model were compared with results based on Malkin's model, which is consistent with measurements reported in Reference 7. This comparison appears to support the validity of Equation 6 as a conservative approximation.

2.2.4 Reduction of Wind Speeds Due to Friction Over Land

The factor for reducing overwater to overland surface wind speeds used in Reference 8 is 0.78 for wind speeds over 37 m/s. In Reference 2, the ratio $V^{\ell}(10)/V^{w}(10)$, where V(10) = 10-min mean speed at 10 m above the surface, and the superscripts w and ℓ indicate "overwater" and "overland", respectively, is given as

$$\frac{V^{\ell}(10)}{V^{w}(10)} = \frac{1}{0.2\ p\ \ln \frac{10}{z_0}} \tag{7}$$

where the retardation factor p = 0.83 and the roughness length z_0 = 0.005 m, so that $V^{\ell}(10)/V^{w}(10) = 0.79$, i.e., this ratio has almost exactly the same value as in Reference 8. Note that Equation 7 is based on similarity relations applicable to storms in which the gradient wind may be regarded as geostrophic, so that its applicability to hurricane winds is uncertain, at least in the region of maximum wind speeds. In this work it was therefore assumed conservatively that $V^{\ell}(10)/V^{w}(10) \simeq 0.85$.

2.2.5 Dependence of Wind Speeds Upon Averaging Time

Research results concerning the ratios of hurricane wind speeds corresponding to different averaging times do not appear to be available. In the absence of such results, it was judged reasonable to use wind speed ratios obtained for non-tropical storms by Durst which are summarized, e.g., in Reference 10, p. 62. For example, the ratio between the fastest one-minute and the fastest 10-minute speed at 10 m above open terrain was assumed to be 1.18.

Facing page: *Trees uprooted by typhoon in Manila (The Philippines).*

3. PROBABILITIES OF OCCURRENCE OF HURRICANE WIND SPEEDS

3.1 THEORETICAL APPROACH

To estimate probabilities of occurrence of hurricane wind speeds, one thousand hurricanes were assumed to hit the area adjoining each of the 56 sites being investigated. (Recall that this area was defined previously in the section "Probabilistic Models", items 6 and 7.) Four categories of storms were considered: entering hurricanes (i.e., hurricanes moving inland), exiting hurricanes (i.e., hurricanes headed toward the ocean after moving over land), upcoast heading hurricanes (i.e., hurricanes whose center remains offshore and moving upcoast), and downcoast heading hurricanes. For each location, the ratios between the number of hurricanes belonging to each of these categories and the total number of hurricanes affecting that location were estimated from the information given in References 3 and 5.

The climatological data for each of the one thousand hurricanes were determined from the respective probability distributions by Monte Carlo simulation (random sampling). Associated with each hurricane is a wind field, and a set of wind speeds at the site of interest which depend

upon the position of the moving hurricane center with respect to the site. These wind speeds were calculated for a sufficiently large number of such positions (6 or 7, depending on track). The largest among these speeds represents the maximum wind speed caused by the hurricane at the site. A set of one thousand such wind speeds is thus obtained, which is used as the basic set of data for the estimation of the probability of occurrence of hurricane wind speeds at the site. (This procedure was applied to estimate extreme wind speeds without regard to direction, as well as extreme wind speeds blowing in specified directions.) The wind speeds are ranked by magnitude, and the probability of occurrence of the i-th ranking wind speed, v_i, in a set of m wind speeds (m = 1,000 in the work reported herein) is obtained as follows.

Let the probability that the wind speed in any one storm is less than v be denoted by F_v. The probability that the highest wind speed V in n storms is less than v can be written as

$$P(V < v|n) = (F_v)^n = F_v^n \tag{8}$$

Let the probability that V < v in τ years be denoted by P(V < v, τ). It is possible to write

$$P(V < v, \tau) = \sum_{n=0}^{\infty} P(V < v|n)\, P(n, \tau) \tag{9}$$

where P(n,τ) denotes the probability that n storms will occur in τ years. If a Poisson process is assumed to describe P(n,τ), and if use is made of Equation 9,

$$\begin{aligned} P(V < v, \tau) &= \sum_{n=0}^{\infty} F_v^n \frac{(\nu\tau)^n}{n!} e^{-\nu\tau} \\ &= e^{-\nu\tau} \sum_{n=0}^{\infty} \frac{(\nu\tau F_v)^n}{n!} \\ &= e^{-\nu\tau} e^{\nu\tau F_v} \\ &= e^{-\nu\tau(1-F_v)} \end{aligned} \tag{10}$$

where the Poisson parameter ν = annual rate of occurrence of hurricanes in the area of interest for the site being considered. For τ = 1, P(V < v, τ) = probability of occurrence of wind speeds less than v in any one year.

Consider now the wind speed v_i. Its probability of occurrence can be written as

$$F_{v_i} = \frac{i}{m + 1} \tag{11}$$

Thus

$$P(V < v_i, 1) = e^{-\nu(1 - \frac{i}{m + 1})} \tag{12}$$

The estimated mean recurrence interval of the speed v_i is then

$$N = \frac{1}{1 - e^{-\nu(1 - \frac{i}{m + 1})}} \tag{13}$$

3.2 NUMERICAL RESULTS

3.2.1 Extreme Wind Speeds

Hurricane fastest-mile wind speeds at 10m above ground over open terrain were estimated for 58 mileposts (from 150 through 3000 in increments of 50 - see Figure 1) at the coastline, and at 25 km, 50 km, 100 km and 200 km inland. The results of the calculations were smoothed as follows. For each milepost the average was calculated of the fastest-mile wind speeds at that milepost and at its two neighboring mileposts [located each at 50 n.mi. (93 km) from it]. This averaging was done, for each milepost, at the coastline, as well as at 25 km, 50 km, 100 km, and 200 km inland. A least-squares straight line was fitted at each milepost to the five averages thus obtained. The ordinates of this line at the coastline and at 200 km inland represent the values given by the curves of Figures 5 and 6, respectively. Extreme fastest-mile speeds at distances inland of less than 200 km from the coastline may be obtained by linear interpolation between Figures 5 and 6. It is noted that the values of Figures 5 and 6 differ by at most a few percent from the corresponding unsmoothed values originally calculated for the coastline locations.

The results shown in Figures 5 and 6 represent smoothed estimates of hurricane wind speeds without regard to direction. As previously indicated, similar results were obtained for winds blowing in specified directions. Estimates of coastline fastest-mile hurricane wind speeds at 10 m above ground over open terrain, smoothed by averaging results obtained for three consecutive milestone positions, are plotted in Appendix A as a function of direction. Note that the number of storms associated with strong winds blowing in specified directions is in certain cases very small. It was therefore not possible in those cases to estimate wind speeds corresponding to relatively short mean recurrence intervals. This is reflected by the blank portions of some of the curves of Appendix A.

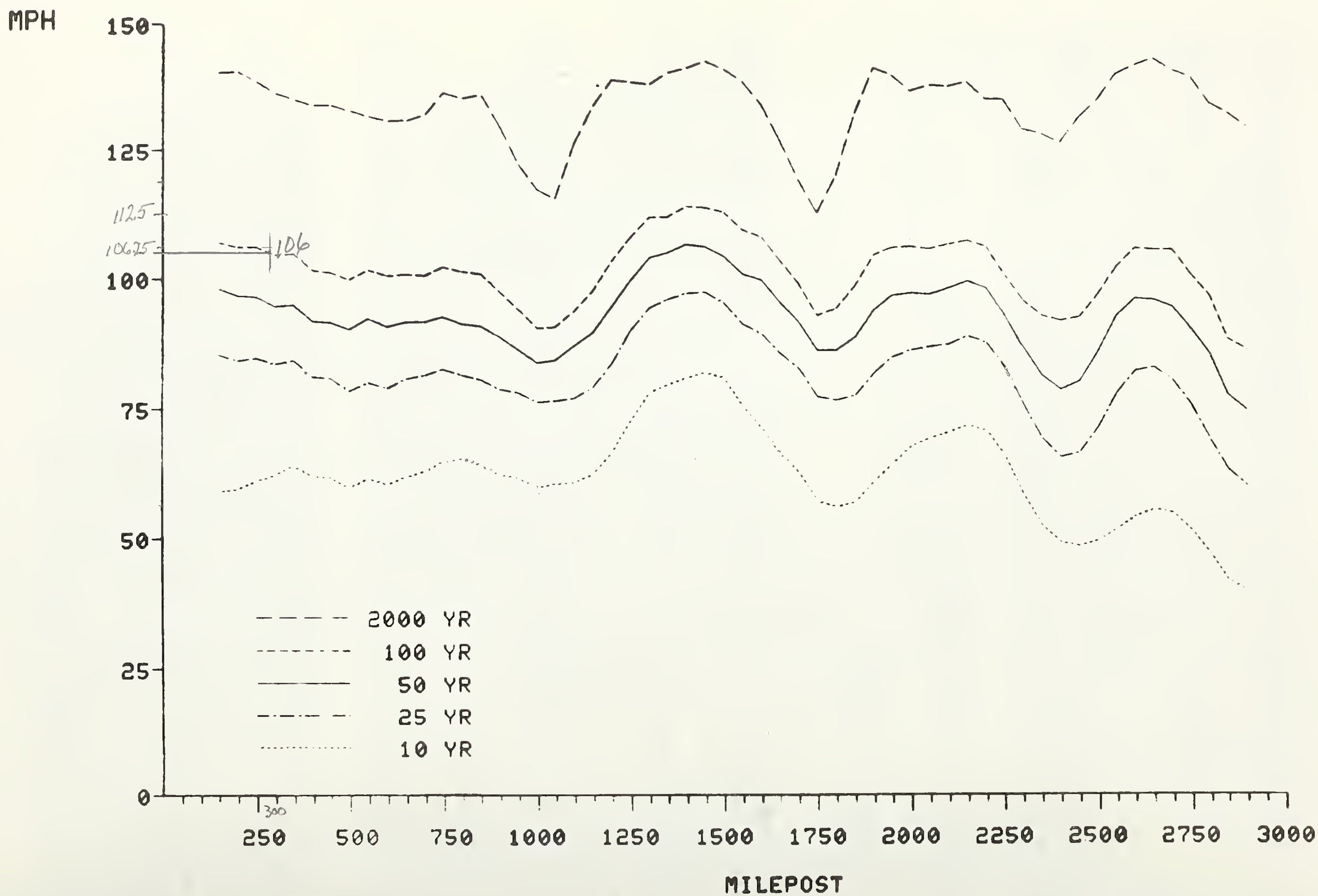


Figure 5. Estimated fastest-mile hurricane wind speeds blowing from any direction at 10 m above ground in open terrain near the coastline, for various mean recurrence intervals (1 mph = 0.47 m/s).

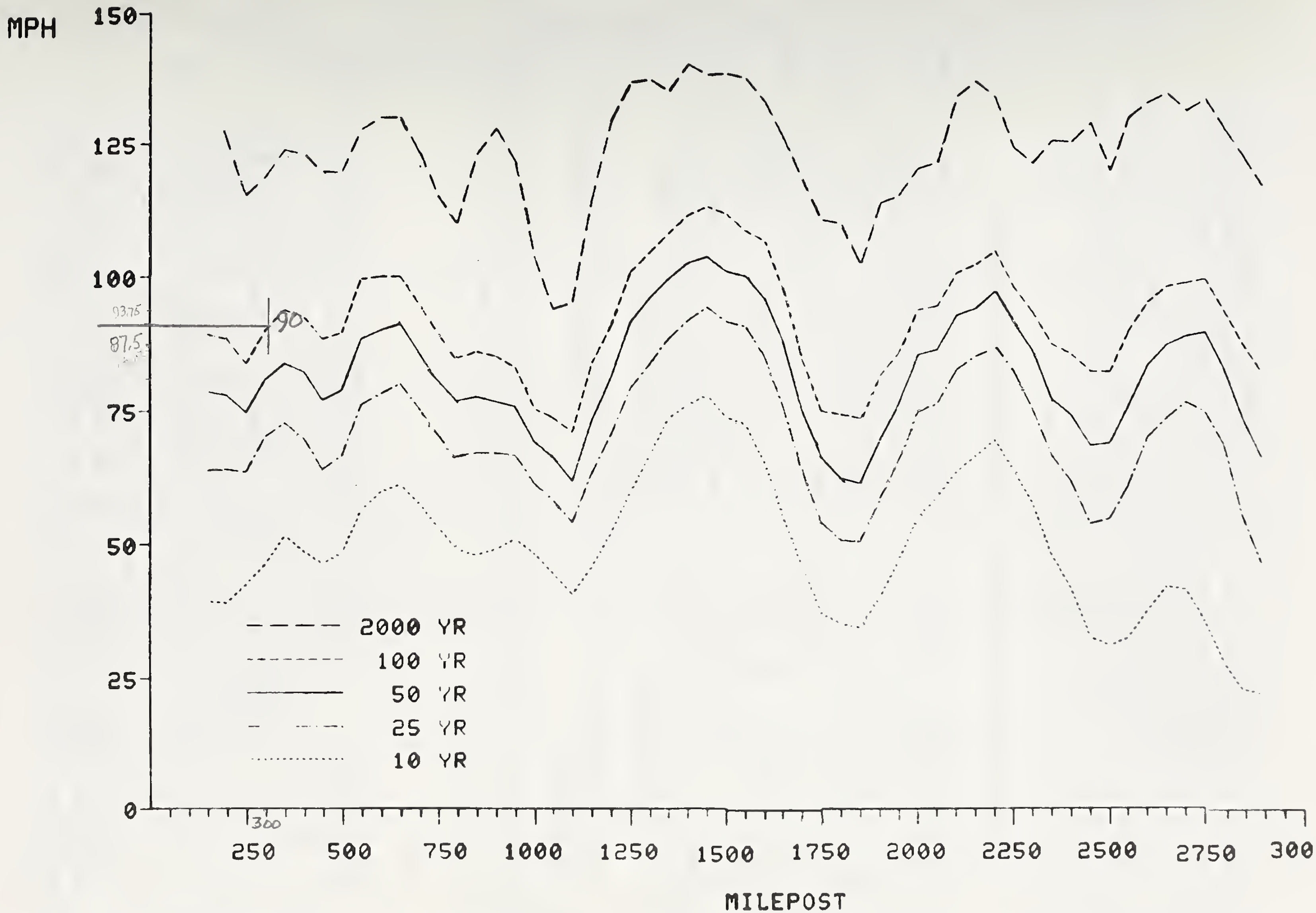


Figure 6. Estimated fastest-mile hurricane wind speeds blowing from any direction at 10 m above ground in open terrain at 200 km inland, for various mean recurrence intervals (1 mph = 0.47 m/s).

Errors in the estimation of extreme hurricane wind speeds are dealt with in the subsequent section. It is noted here that these errors increase as the mean recurrence interval increases. Therefore, estimates of wind speeds corresponding to mean recurrence intervals exceeding 100-yr, say, may contain significant errors. Nevertheless, such estimates obtained by the procedure used in this paper are of interest as they provide the only available basis for assessing the validity of wind load factors currently being used for structural design purposes in hurricane-prone regions.

3.2.2 Probability Distributions of Hurricane Wind Speeds

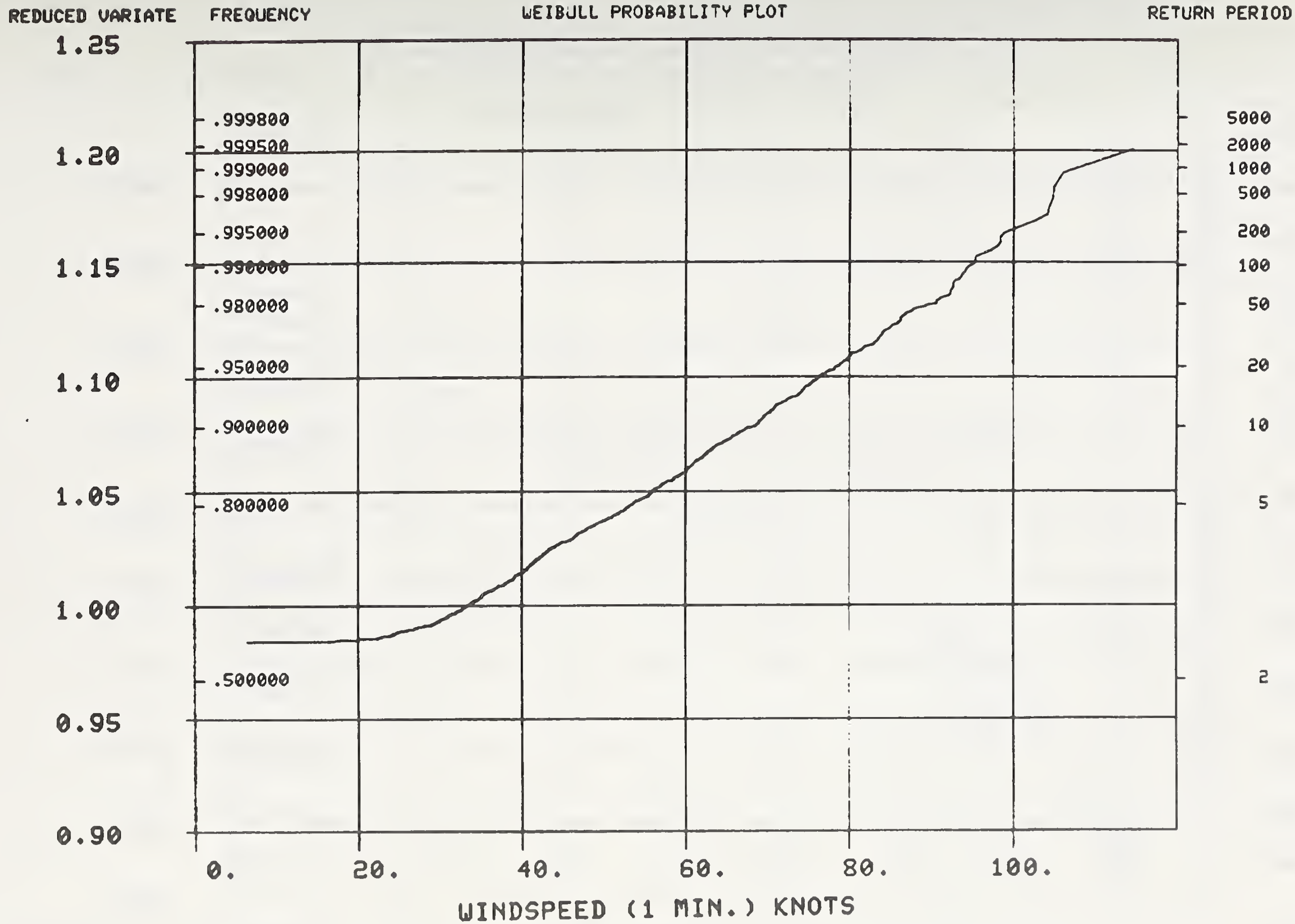
The results obtained from the calculations were used to estimate probability distributions of hurricane wind speeds (blowing from any direction). It was found, by using the probability plot correlation coefficient method, that in all cases the best fitting distribution for the 1-minute speeds was the Weibull distribution with tail length parameter $\gamma > 4$ (for practical purposes $\gamma = 4$ can be assumed, the differences between results based on $\gamma = 4$ and $\gamma > 4$ being negligible). As an illustration, the results obtained at milepost 450 [1-minute wind speeds at coastline over water, in knots (1 knot $\simeq$ 1.9 km/hr)] are plotted on Weibull(γ=4) and Extreme Value Type I probability paper on Figures 7 and 8, respectively. It is seen that the results fit the Extreme Value Type I distribution poorly, i.e., the results do not fit a straight line on Fig. 8, as they do on Fig. 7.

3.3 MIXED PROBABILITY DISTRIBUTIONS OF HURRICANE AND NON-HURRICANE WIND SPEEDS

Mixed probability distributions of hurricane and non-hurricane fastest-mile (as opposed to 1-minute) wind speeds were estimated by using the following expression:

$$P(V < v) = P_H\,(V_H < v) \cdot P_{NH}(V_{NH} < v) \tag{14}$$

in which $P_H\,(V_H < v)$ = cumulative distribution of hurricane wind speeds V_H, and $P_{NH}\,(V_{NH} < v)$ = cumulative distrtibution of non-hurricane wind speeds, V_{NH}. The distribution P_H was determined as shown in this report. For the distribution P_{NH}, an Extreme Value Type I distribution was assumed. The parameters of P_{NH} were estimated at various locations from maximum annual wind speed data that did not include hurricane wind speeds. The results of the calculations showed that the effect of the non-hurricane winds is negligible for mean recurrence intervals of the order of 50 years or more (see Fig. 9). For mean recurrence intervals of about 20 years, the estimated wind speeds that include the effect of non-hurricane winds exceed the estimated hurricane speed by about 5%. Note that these conclusions are not applicable north of Cape Hatteras, where non-hurricane wind may control the design at certain locations.



Fig, 7 Weibull probability distribution plot of 1-min hurricane wind speeds, milepost 450 n. mi. (Tail length parameter of the distribution: γ = 4)

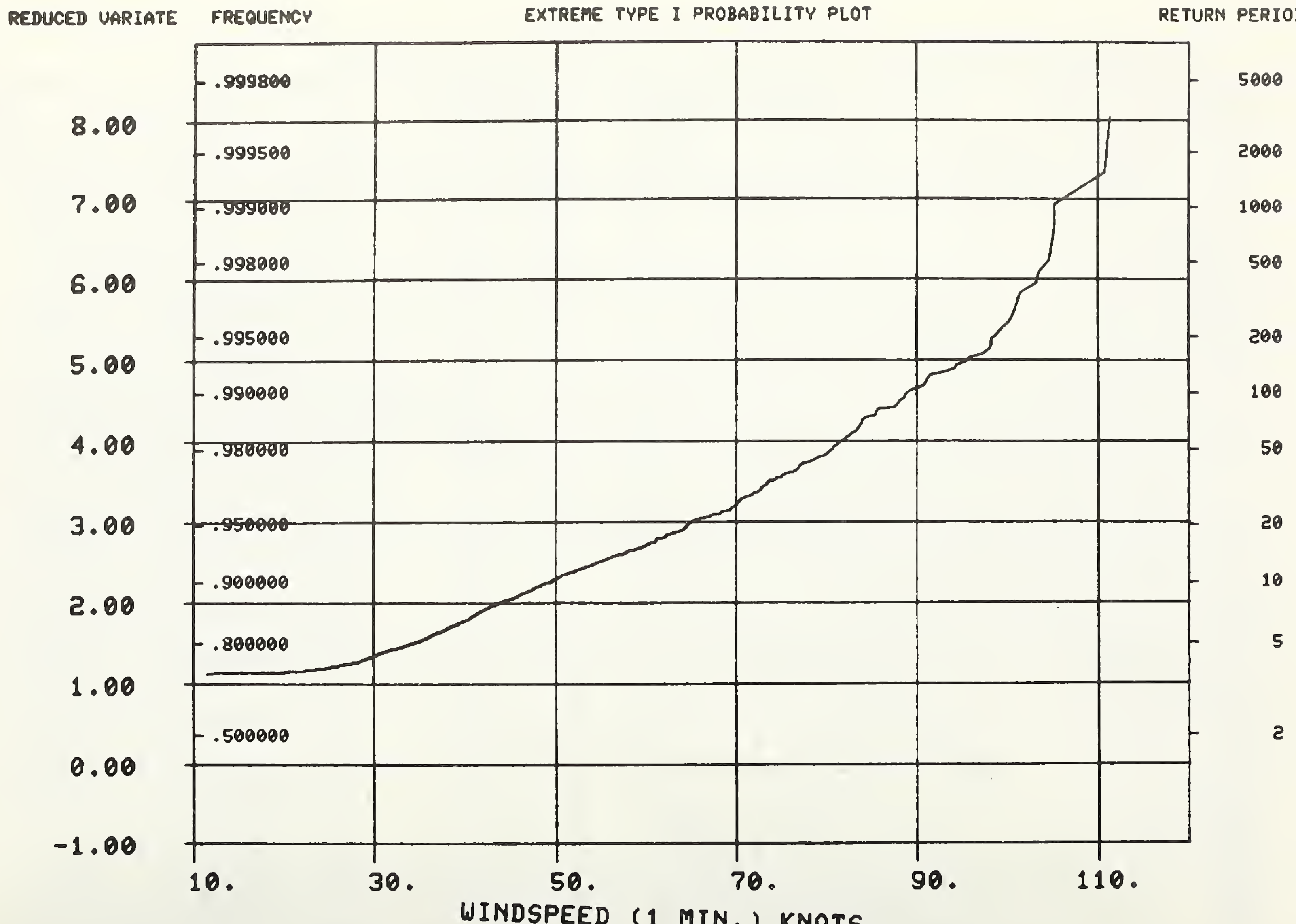


Figure 8. Extreme value Type I probability distribution plot of 1-min hurricane wind speeds, milepost 450 n. mi.

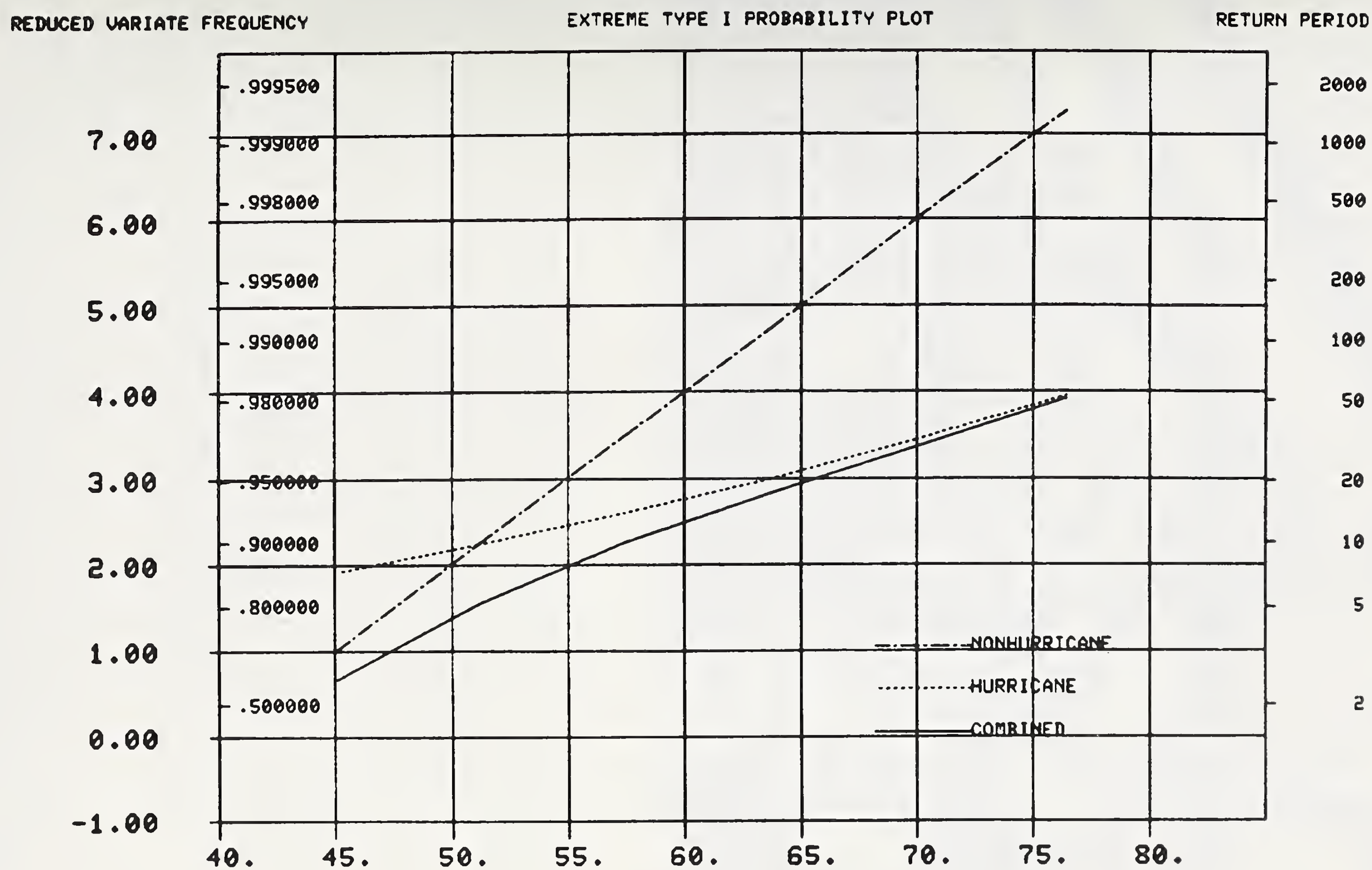


Figure 9. Extreme value Type I probability distributions of fastest-mile wind speeds (mph).

Facing page: *Damage caused by Cyclone Tarcy in Darwin, Australia.*

4. ESTIMATION ERRORS

The errors in the estimation of hurricane wind speeds by the procedure used in this work may be divided into four categories: (1) sampling errors, due to (a) the limited size of the data sample used in making statistical inferences on the climatologogical characteristics of hurricanes (in the United States these data samples correspond to lengths of record of 75 to 100 years), and (b) the limited number of hurricanes generated by the Monte Carlo simulation; (2) probabilistic modeling errors, due to the imperfect choice of the distribution functions to which the climatological data are fitted (e.g., assuming that a lognormal distribution holds when in fact a normal distribution would be more appropriate); (3) observation errors, due to the imperfect measurement or recording of the true values of the climatological characteristics; and (4) physical modeling errors, due to the imperfect representation of the dependence of the wind speed upon the various climatological characteristics and micrometeorological parameters.

4.1 SAMPLING ERRORS

As shown in some detail in Reference 1, the standard deviation of the errors associated with the limited size of the climatological data samples (corresponding to about 75 to 100 years of record) is of the

order of 6% to 10% of the estimated wind speeds, while the standard deviation of the errors due to the limited number, m, of hurricanes used in the simulation is of the order of a few percent for m $\sim$ 1,000. In some cases, say, at Jacksonville, Florida, the poorly understood and seemingly anomalous occurrence histories may lead to larger errors than are typical of the model overall. Part of the sampling errors due to the limited number of hurricanes used in the simulation is eliminated by the use of the smoothing procedure described previously.

4.2 PROBABILISTIC MODELING ERRORS

To assess the effect of various probabilistic models used in the simulation, calculations were carried out at mileposts 400, 1450 and 2100 (see Figure 1) under the following assumptions:

a. Distribution of Δp_{max} is normal. This assumption results in a decrease of the 50-yr, 100-yr, and 400-yr wind speeds with respect to the corresponding values based on the assumption of lognormality by about 5%, 5%, and 8%, respectively.

b. Distribution of R is normal. This assumption results in an increase of the 50-yr, 100-yr, and 400-yr wind speeds with respect to their corresponding values based on the assumption of lognormality by about 1%, 2%, and 6%, respectively.

c. Distributions of Δp_{max} and R are both normal. This assumption results in a decrease of the 50-yr, 100-yr, and 400-yr wind speeds with respect to their corresponding values based on the assumption that Δp_{max} and R are both lognormally distributed by about 3%, 3%, and 4%, respectively.

d. Distribution of s is lognormal. The differences between estimates of wind speeds based on this assumption on the one hand, and on the assumption that s is normally distributed on the other hand, are negligible for practical purposes.

e. Distribution of Δp_{max} is not censored. The censoring of the distriibution of Δp_{max} ($\Delta p_{max} < 101.6$ mm) reflects the writers' belief that this upper bound is dictated by physical considerations, and that an unbounded distribution would thus be physically unrealistic. Nevertheless, calculations were carried out for five stations in which it was assumed that the lognormal distribution of Δp_{max} is unbounded. It was found that the estimated hurricane wind speeds and their cumulative distribution functions were for practical purposes the same regardless of whether the condition $\Delta p_{max} < 101.6$ mm was assumed or not.

A final observation with regard to the choice of probabilistic models concerns the representation of the hurricane occurrences as a Poisson process. It can be shown that this model could be replaced, e.g., by a geometric probability model, without any significant effect upon the estimated results, particularly for winds with mean recurrence intervals of the order of 20 years or more.

4.3 OBSERVATION ERRORS

To assess the effect of possible errors in the measurement (or recording) of the parameters Δp_{max} and R, calculations were carried out at mileposts 400, 1450, and 2100 (Figure 1) in which it was assumed that the mean and/or standard deviation of Δp_{max} and R are larger than those estimated from the data of Reference 5. Increasing both the mean and the standard deviation of Δp_{max} by a factor of 1.1 resulted in an increase in the estimated values of the 50-yr, 100-yr, and 400-yr winds of about 5% at milepost 400, 8% at milepost 1450, and 10% at milepost 2100. Leaving the mean unchanged and increasing the standard deviation by a factor of 1.1 resulted in an increase of the estimated speeds of the order of a few percent. The effect of increasing or decreasing the mean and/or the standard deviation of the radii of maximum wind speeds, R, by a factor as high as 1.5 was of the order of a few percent at most.

As previously indicated, the data used in this report were obtained from Ref. 5. The estimation of hurricane wind speeds at various locations could presumably be improved by using additional sources of climatological information, e.g., those available in the archives of the Corps of Engineers. The writers believe that this is the case particularly for South Texas, Louisiana, southwest Florida and Jacksonville.

Note that estimated hurricane wind speeds are lower at mileposts 1000 and 1750 (Figures 1, 5, and 6) than in the regions adjacent to these mileposts. This may be due to the relation between configuration of the coast and the hurricane paths. However, it may be that hurricanes at and near these mileposts were underreported in the past. It appears therefore prudent to increase the wind speeds calculated at mileposts 1000 and 1750 by about 5 mph or 10 mph. Finally, it was found that the storm decay overland was very weak at mileposts 650 and 2250. This is due, at least in part, to the configuration of the coast at these mileposts, although the spurious occurrence of strong simulated storms may also have contributed to this result.

4.4 PHYSICAL MODELING ERRORS

The coefficient K in Equation 3, the coefficients of Equation 4, and the dependence of wind speeds upon radius represented in Figure 4, have been determined empirically by the National Weather Service on

the basis of careful correlations of pressure and wind speed measurements. Clearly, the corresponding physical model of the hurricane wind field is, nevertheless, imperfect. It is the writers' belief, based, e.g., on information from Reference 6, that the standard deviation of the errors inherent in this model is of the order of 5% to 10%.

It was noted previously that the coefficient K assumed in this work may be used in conjunction with the value p_n = 756 mm (29.77 in). To check the effect on the calculated results of the assumption p_n = 760 mm (29.92 in), calculations based on this assumption were carried out at mileposts 400, 1450, and 2100. It was found that differences between results based on p_n = 756 mm and p_n = 760 mm were of the order of 3%.

It was also noted that results based on the model for storm decay used in this work (Equation 6) were compared with results based on Malkin's model, which is consistent with measurements reported in Reference 7. The differences between the two sets of results were in all cases small (of the order of $\pm$ 2%).

In estimating wind speeds over water immediately off the shoreline it was assumed that the roughness length parameter corresponds to "flow over water" conditions in all directions (this will be referred to as "surface friction hypothesis I"). In reality, each location immediately offshore is affected not only by hurricane winds which blow from the ocean (and for which "flow over water" conditions prevail), but also by hurricane winds blowing from inland, for which the assumption that a roughness length corresponding to "flow over open terrain" conditions may have to be used. The hypothesis that the roughness length depends upon whether the winds flow from the ocean or from land will be referred to as "surface friction hypothesis II". Whether or not "surface friction hypothesis II" is warranted is by no means always certain: indeed, near the shoreline the terrain is likely to be flooded during the occurrence of hurricanes. Nevertheless, it is of interest to check the differences between results based on surface friction hypotheses I and II. Calculations carried out at mileposts 400, 850, 1450, 2100, and 2800 showed that estimated wind speeds corresponding to hypothesis II were lower than those based on hypothesis I by an amount generally not exceeding 3%.

Local wind intensification due to the presence of rainbands occur at all locations south of the 30° north parallel. These intensifications might have to be be accounted for by increasing the wind speeds calculated herein by as much as 10 mph (4.47 m/s) or so.

As previously noted, the physical models used in this report, and particularly the storm decay model, provide a description of the wind field that is probably less accurate at sites located north of Cape Hatteras, N.C., (mileposts 2200 or more, see Figure 1). The numerical results obtained for these sites should therefore be viewed very cautiously.

The physical model of the hurricane wind speeds may be refined by using a detailed representation of the coastline and its adjacent bodies of water. Such refinements may result in an improvement of hurricane wind speed estimate by an amount of the order of 5% or so.

Additional refinements might include accounting for slower storm decay where large bodies of water are present inland, e.g., in the low-lying areas of Louisiana. Additional research is required to develop improved storm decay models in such situations.

Facing page: *Damage caused by Hurricane Camille.*

5. CONCLUSIONS

In this paper, estimates are presented of hurricane wind speeds along the Gulf and East Coasts of the United States. The paper describes the sources of data, the probabilistic models for the climatological characteristics of hurricanes and the physical models for the hurricane wind speed field used in the estimations. Estimated values of fastest-mile hurricane wind speeds at 10 m above ground in open terrain at the coastline and at 200 km inland are given for various mean recurrence intervals (Figures 1, 5, and 6). Fastest-mile wind speeds at distances inland of less than 200 km from the coastline may be obtained by linear interpolation between these values. It was found that the estimated hurricane wind speeds are best fit by Weibull distributions with tail length parameters $\gamma \geq 4$, rather than, e.g., by Extreme Value Type I distributions. Estimates are given of various errors inherent in the estimated values of the hurricane wind speeds. The confidence bands for the estimates were found to be of the order of at least $\pm$ 10% at the 68% confidence level. It was also noted that, owing to the possible inapplicability of the physical models used in this work at locations north of Cape Hatteras, estimated hurricane wind speeds

given for these locations should be viewed with considerable caution. In certain special cases it may be desirable to base estimates of hurricane wind speeds on more elaborate data, physical models, and representations of the coastline than those used in this work. Nevertheless, in the writers' opinion, the results presented in this paper provide a rational and consistent basis for making realistic decisions on the specification of design wind speeds and load factors in hurricane - prone regions.

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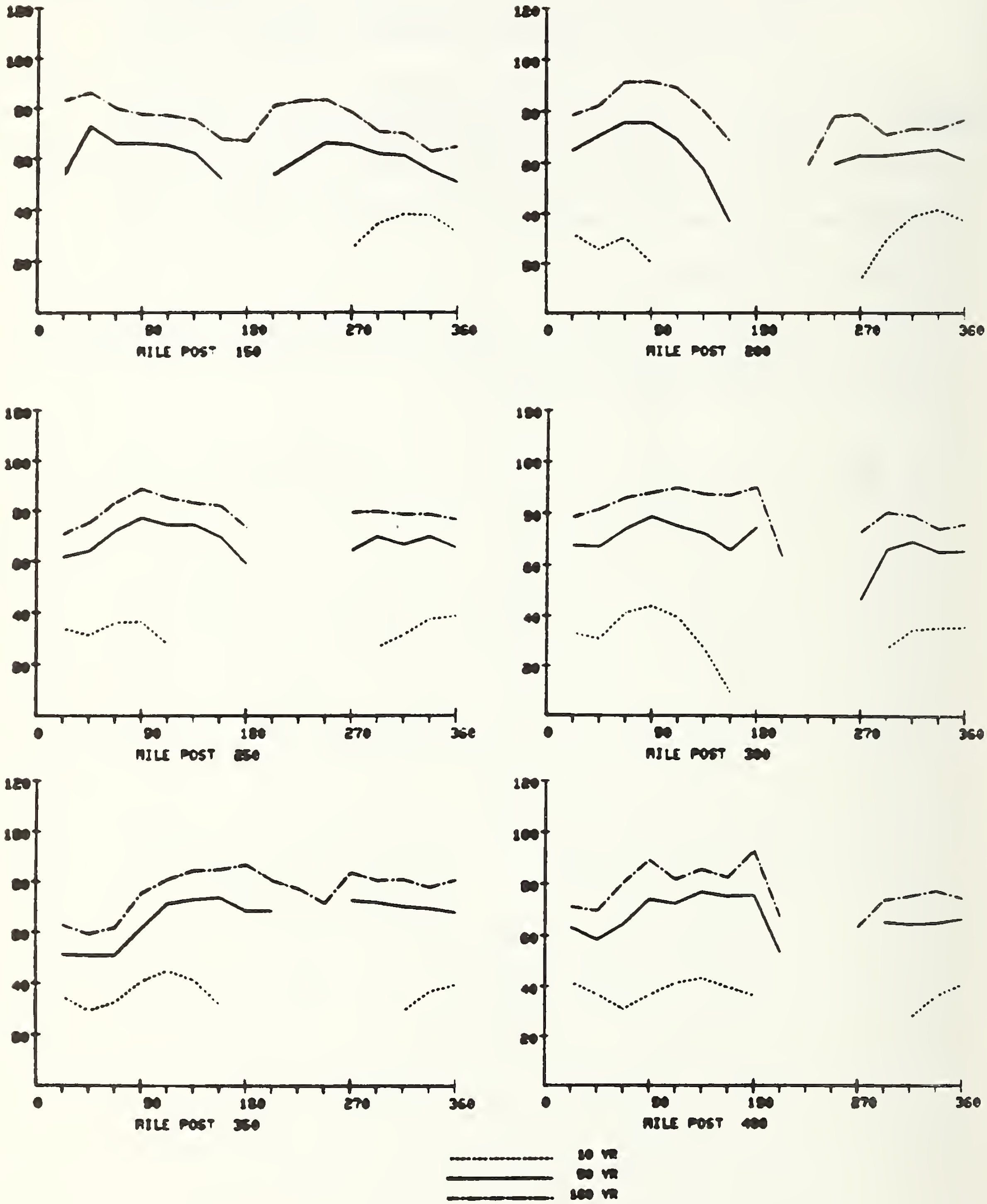
APPENDIX A

HURRICANE WIND SPEEDS BLOWING FROM SPECIFIED DIRECTIONS FOR 10-YR, 50-YR, and 100-YR MEAN RECURRENCE INTERVALS

Notes

1. For key to mean recurrence interval symbols, see bottom of next page.
2. Ordinates represent estimated fastest-mile mean speeds in mph (1 mph = 0.447 m/s).
3. Abscissas represent clockwise angles of directions from which winds are blowing with respect to north.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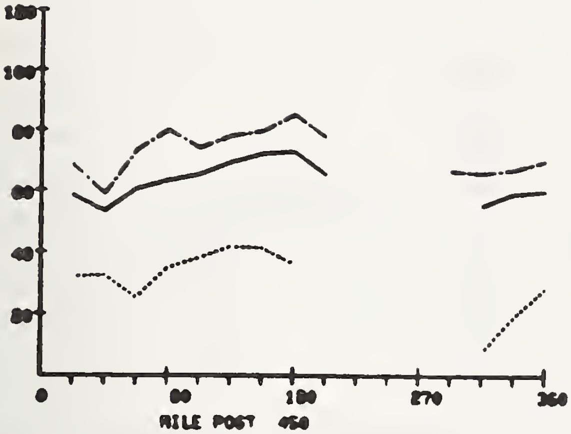
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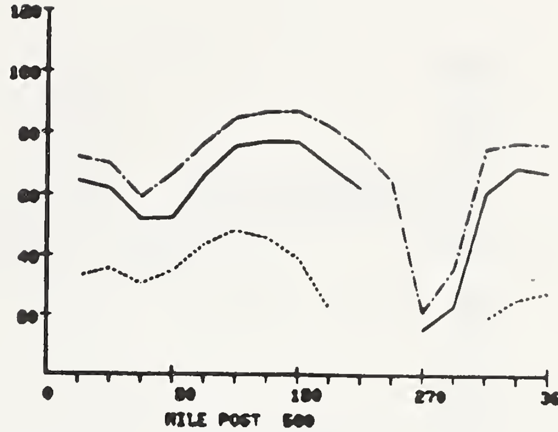
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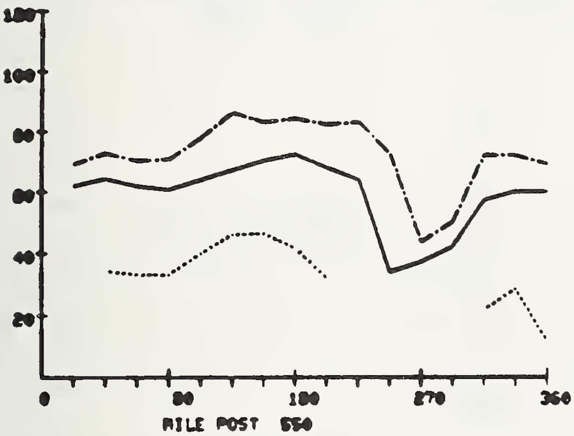
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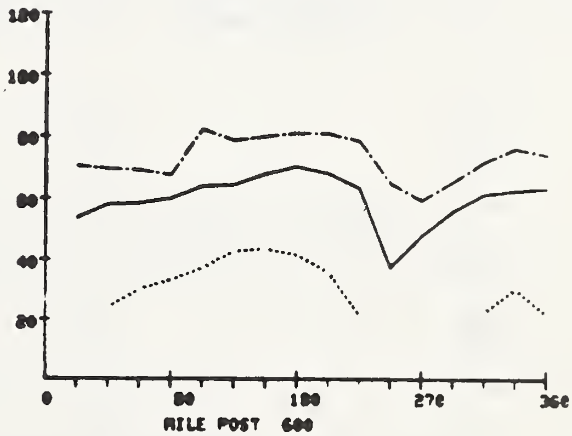
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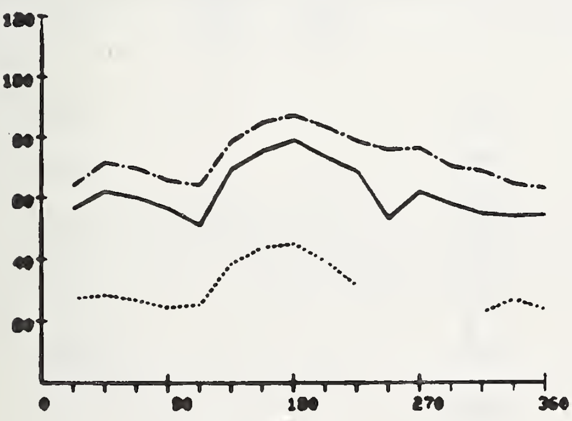
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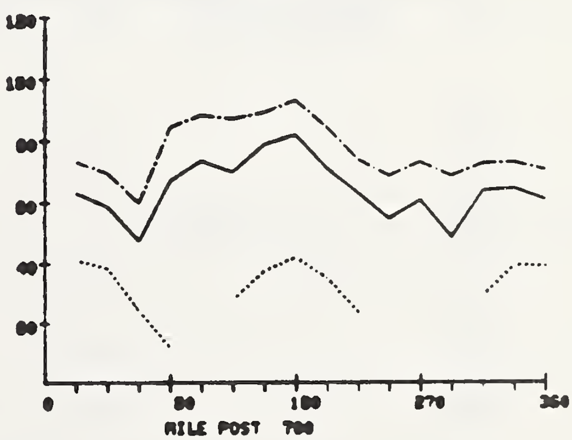
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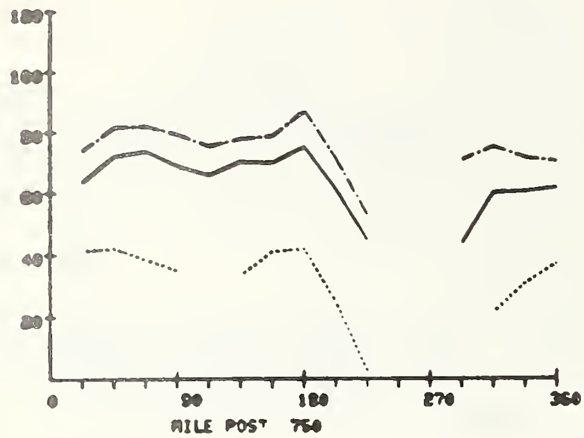
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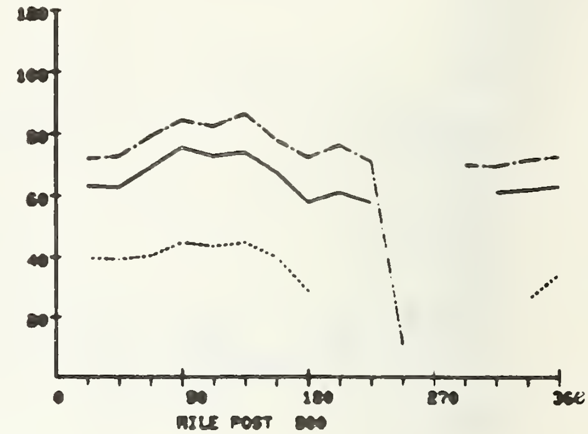
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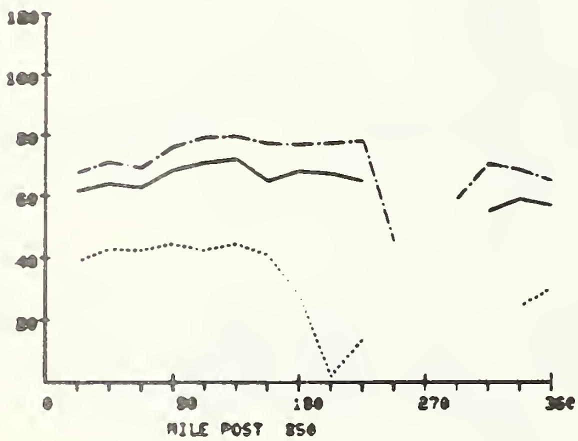
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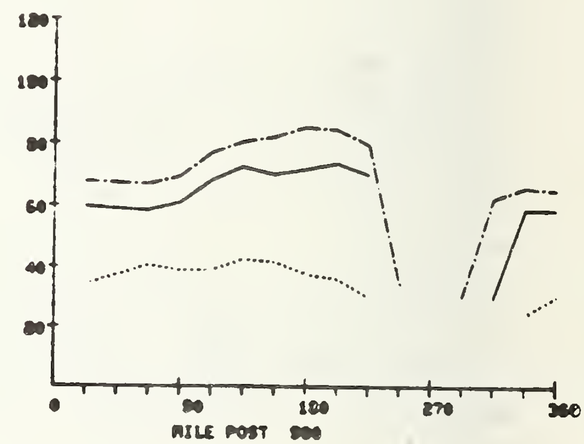
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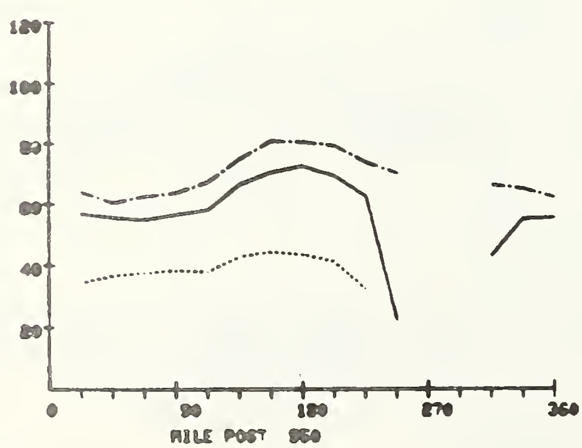
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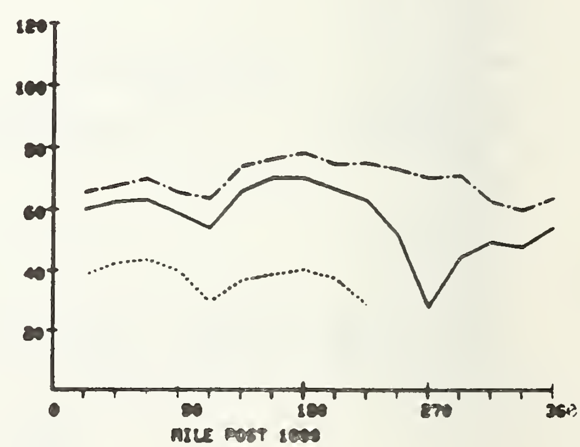
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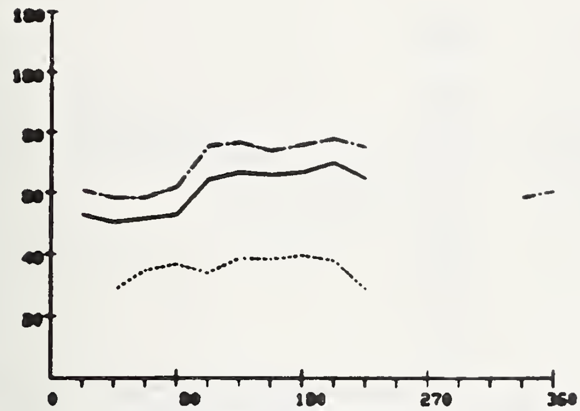

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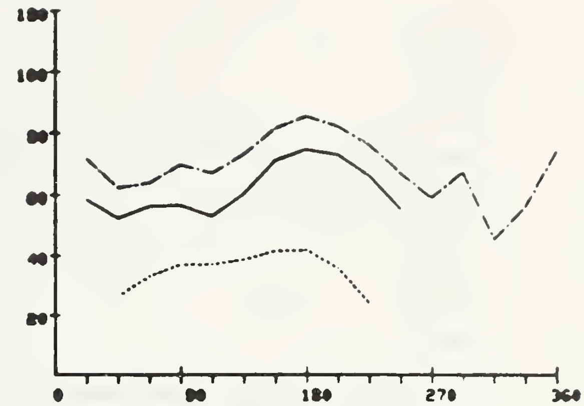

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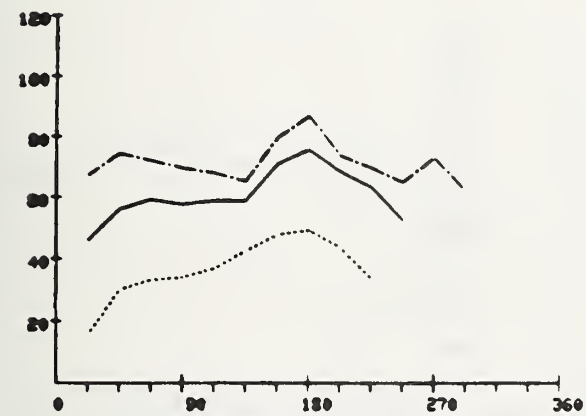

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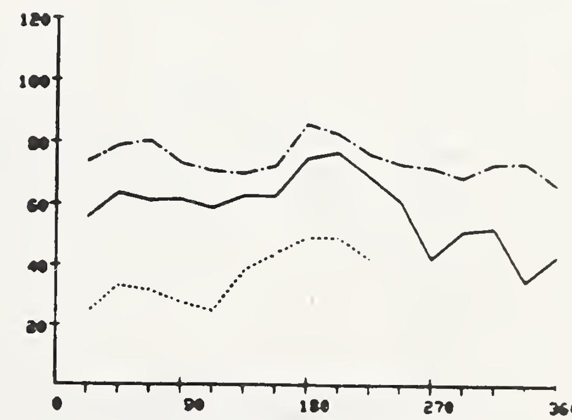

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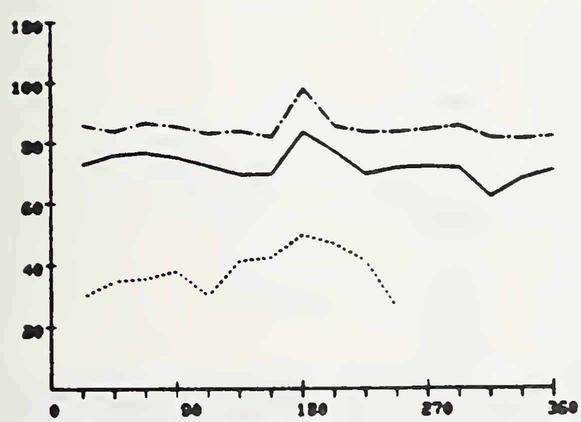

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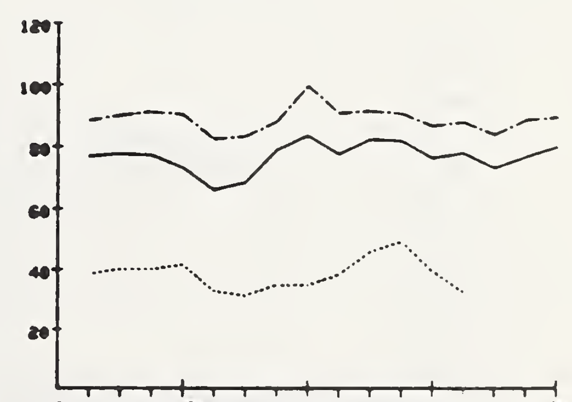

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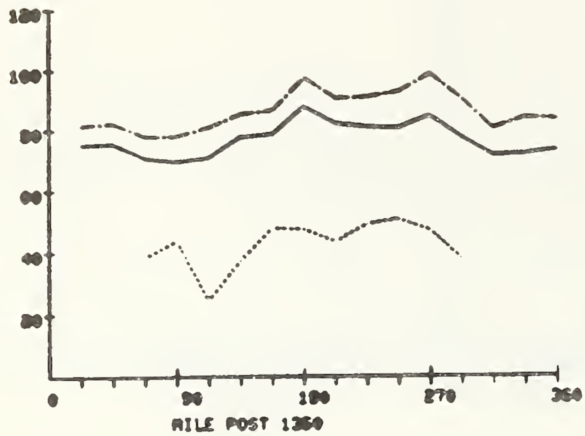
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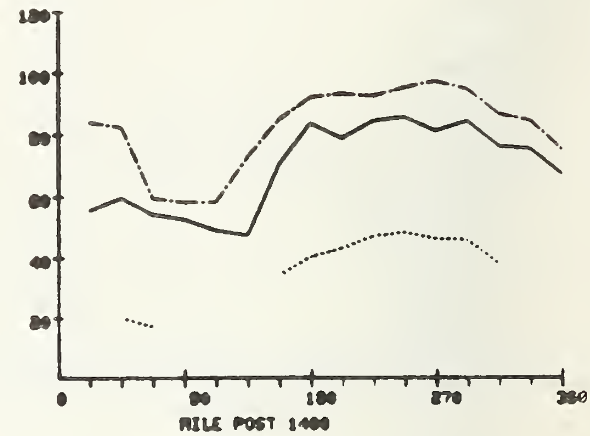
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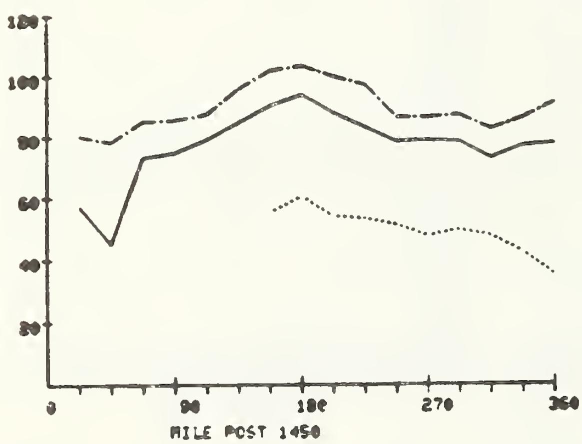
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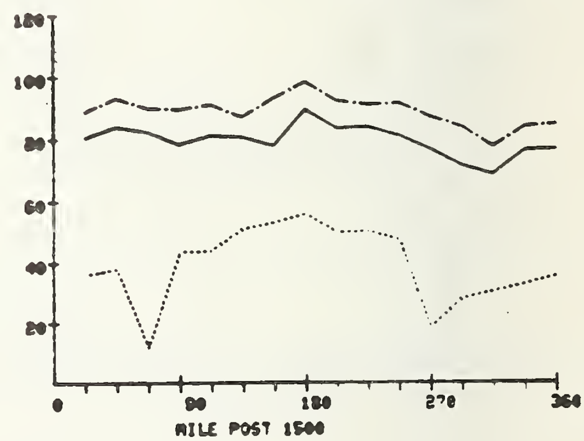
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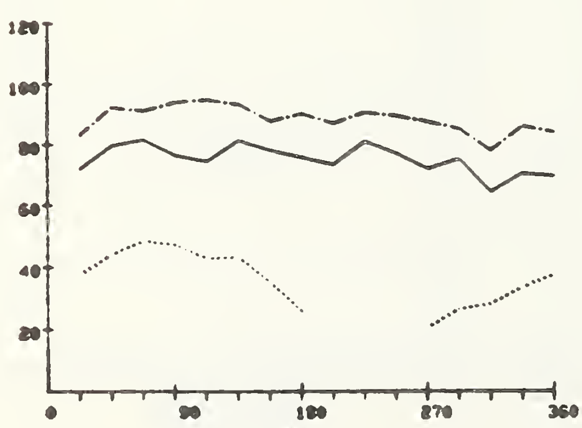
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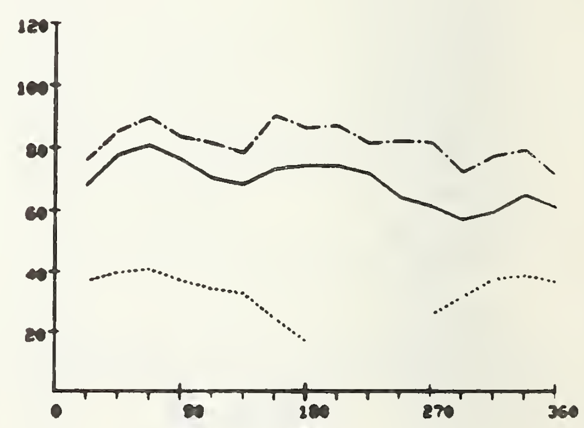
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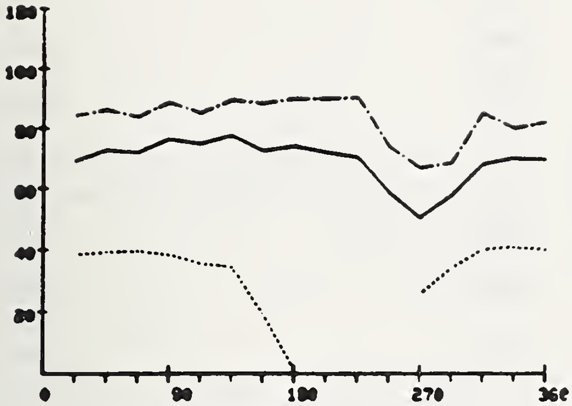

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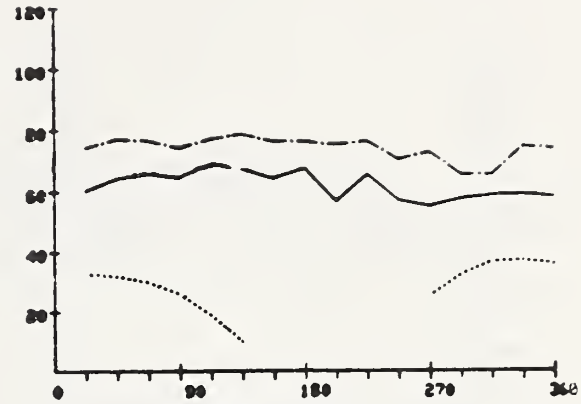

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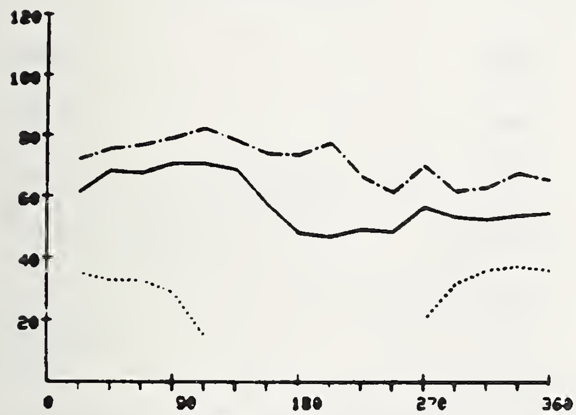

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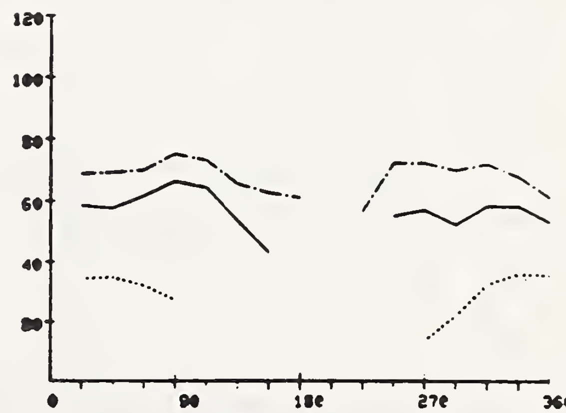

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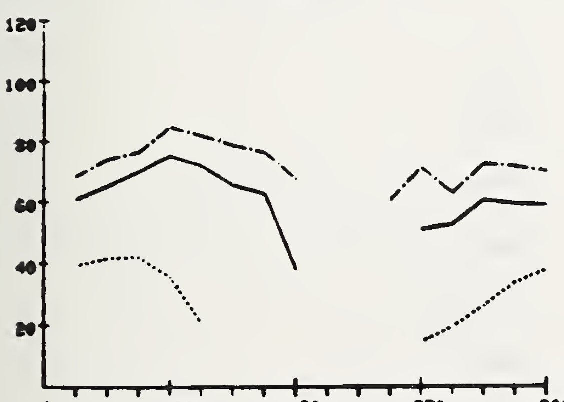

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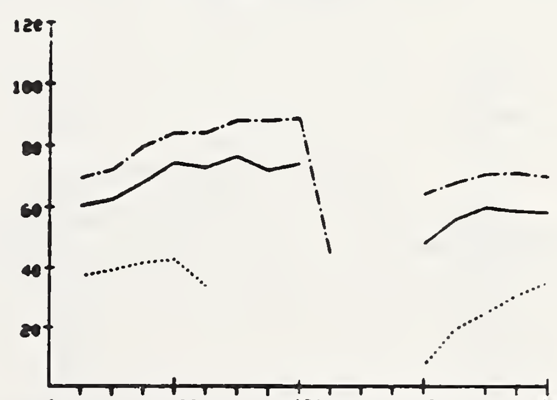

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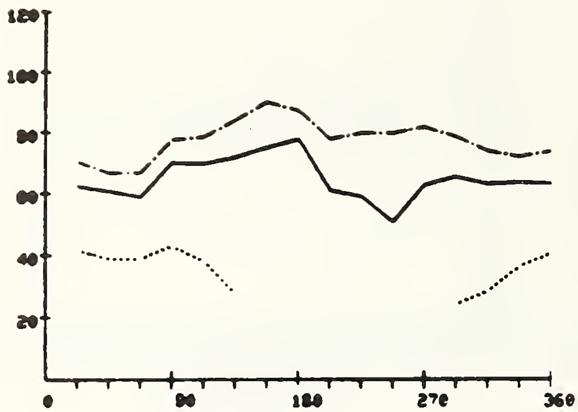

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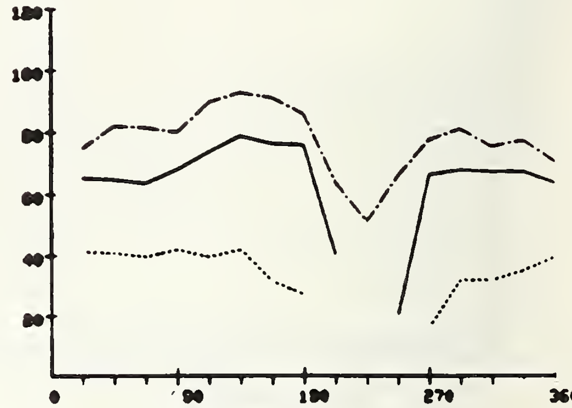

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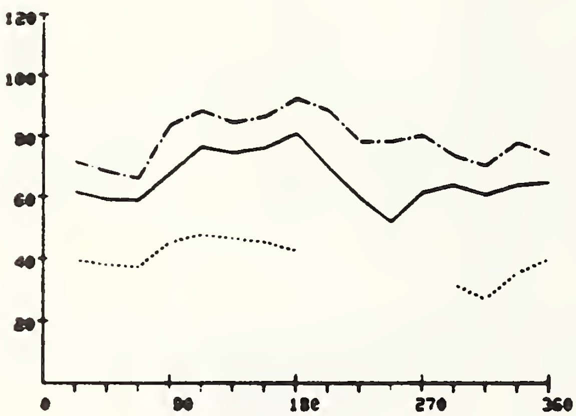

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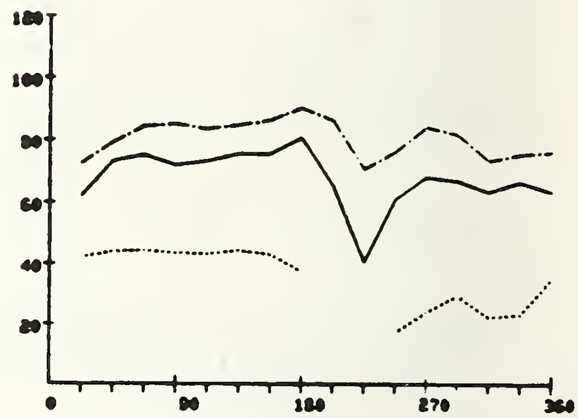

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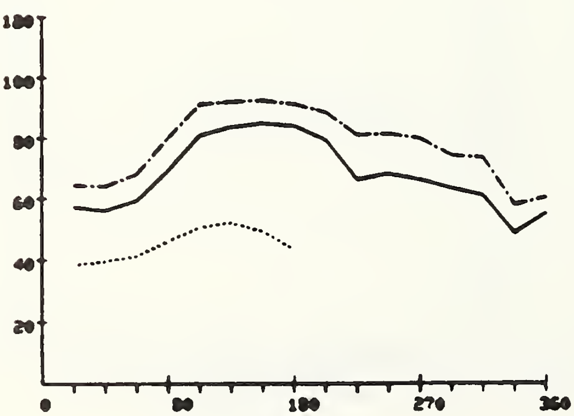

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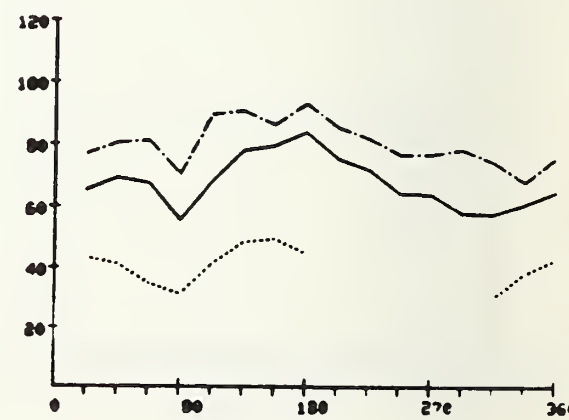

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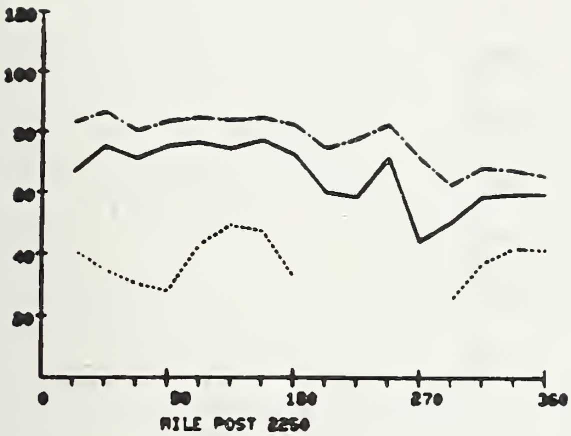
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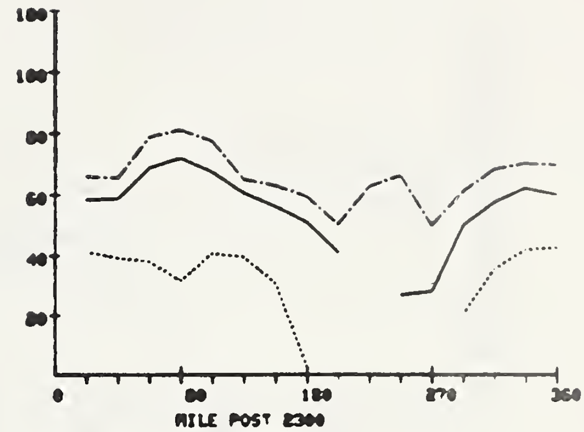
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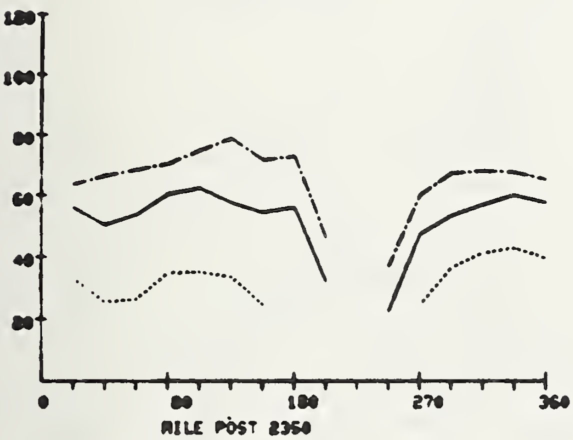
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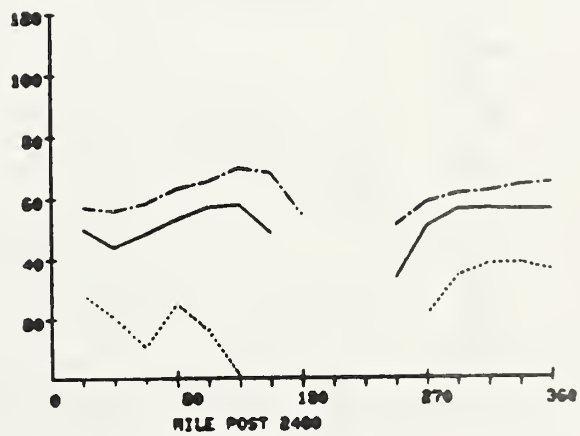
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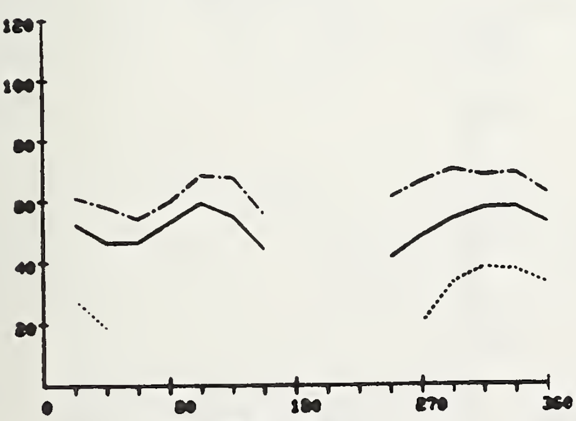
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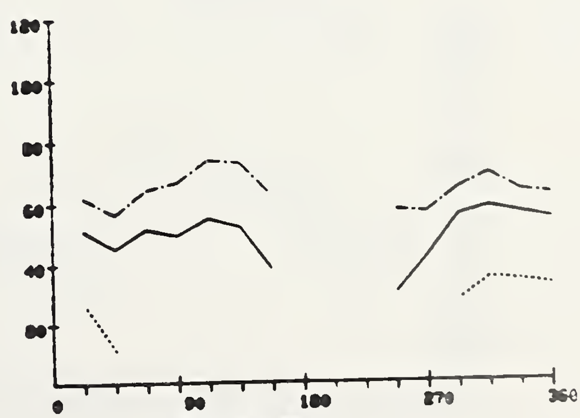
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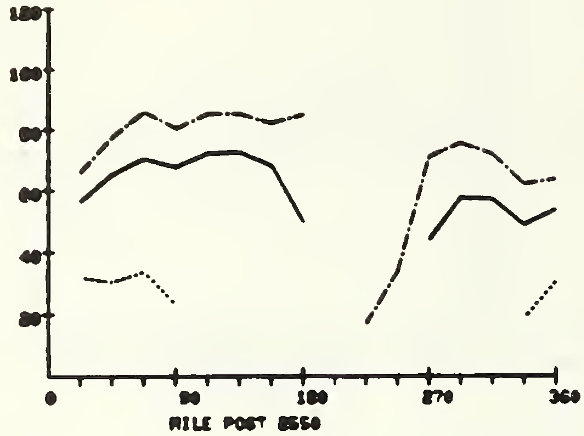
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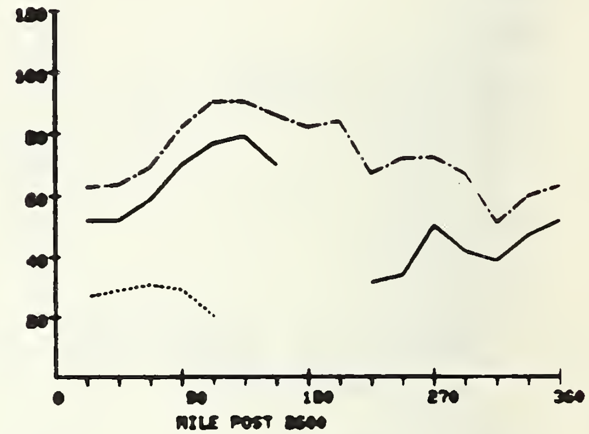
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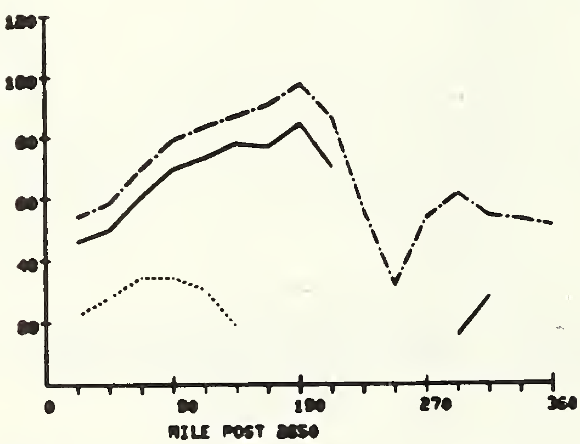
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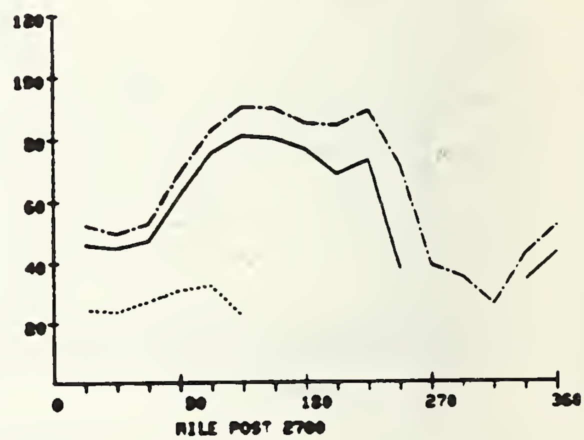
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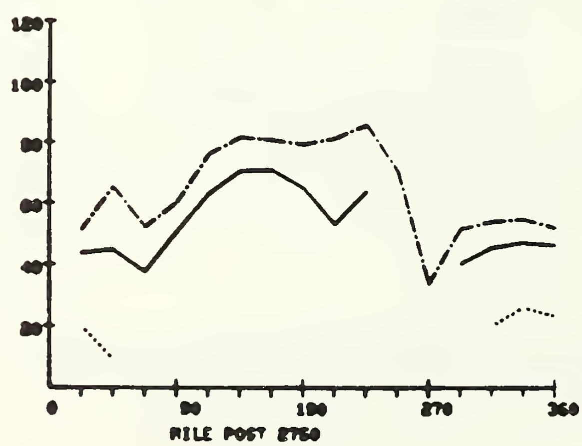
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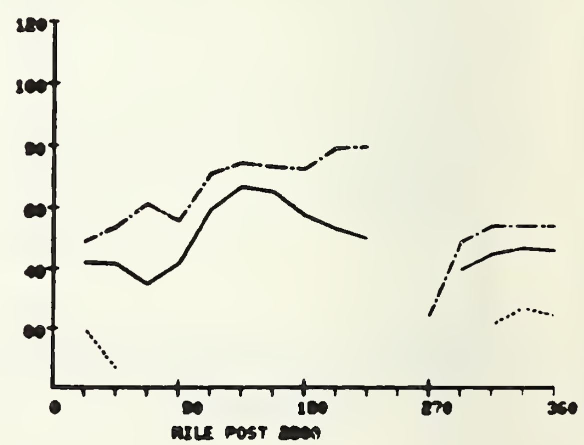
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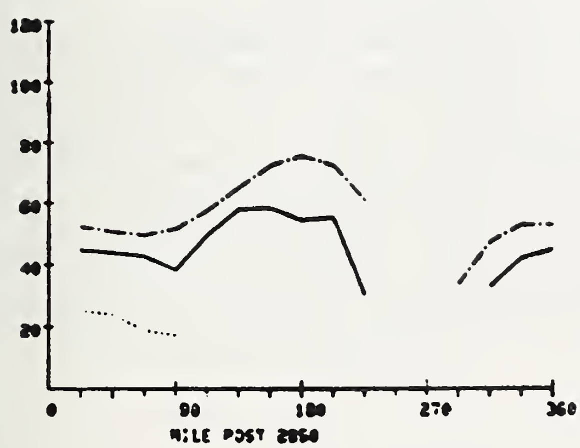

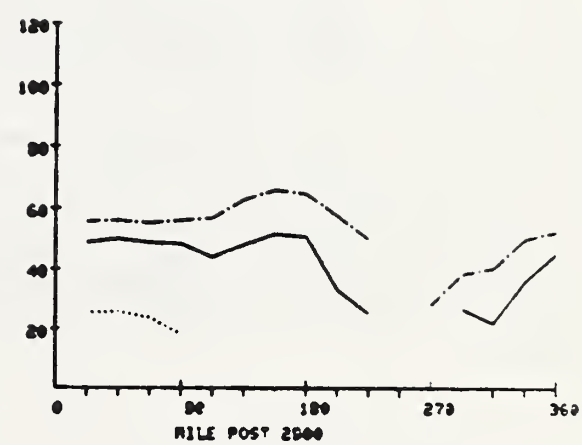

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15. SUPPLEMENTARY NOTES

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

A Monte Carlo simulation technique is used to obtain estimates of hurricane wind speeds in the Gulf and East Coasts of the United States. The paper describes the sources of data, the probabilistic models for the climatological characteristics of hurricanes, and the physical models for the hurricane wind speed field used in the estimations. Estimated values of fastest-mile hurricane wind speeds at 10 m above ground in open terrain at the coastline and at 200 km inland are given for various mean recurrence intervals. The estimated hurricane wind speeds were found to be best fitted by Weibull distributions with tail length parameters $\gamma > 4$. Estimates are given of various errors inherent in the estimated values of the hurricane wind speeds. Owing to uncertainties with respect to the applicability of the physical models used in this work to locations north of Cape Hatteras, estimated hurricane wind speeds given for these locations should be viewed with caution.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* Building (codes); climatology: hurricanes, statistical analysis; structural engineering; tropical cyclones; wind (meteorology).

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